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ABSTRACT

Measurement of various U and Pu samples by gamma-ray spectrometry were performed at the Institute of Physics and Power Engineering to support physical-inventory-taking activities under the Joint US-Russian MPC&A Program. The resulting data was analyzed by several different methods which included Canberra's MGA9.63 (Pu and MOX analysis) and MGAU (U analysis), EG&G Ortec's MGA++ (Pu and MOX analysis) and U235 (U analysis), and FRAM v2.2 (U and Pu analysis) provided by Los Alamos. The results indicate that all of these codes are capable of performing the isotopic analysis adequately. However, some additional modifications may be required to permit better measurement of some of the more unusual components in the Institute of Physics and Power Engineering (IPPE) inventory to meet the demands of inventory-taking activities.

INTRODUCTION

The integrated system of Materials Control and Accounting (MC&A) was created at IPPE about five years ago. The Periodic Inventory Taking (PIT) procedure is a very important part of the total material control and accounting (MC&A) system. A significant part of this procedure is taking nondestructive measurements of controlled items. There are several different systems that are used for Nondestructive Assay (NDA). These include: Fast identifiers of Special Nuclear Material (SNM), systems for precise isotopic determination such as MGA-based methods and FRAM, and neutron coincidence counters for SNM mass determination.

These instruments and techniques are currently utilized in two of the largest Material Balance Areas (MBAs) in IPPE; the Central Storage Facility (CSF) and Big Facility Stand (BFS). There are many types of SNM in the CSF and BFS that require accounting by means of MC&A. These include plutonium metal (^{239}Pu, 88% and 95%) and some PuO_2 (^{239}Pu, 9%, 67%, 77% and 98%). Moreover, there are some Pu samples with large isotopic fractions of ^{238}Pu, ^{240}Pu and ^{241}Pu. Uranium materials are also present in a wide variety of forms including metal, powder, and ceramic items with ^{235}U content ranging from 0.23% to 99.8%. Some items are covered by a 0.3 mm foil and some are in steel containers of varying thickness.

It is very important to test and evaluate NDA instruments and techniques under the operating conditions at BFS and CSF to permit estimation of the applicability of the NDA systems to PIT activities. The large variety of SNM at IPPE and the fact that the materials are very different than materials in the U.S. inventory makes NDA evaluation activities such as those presented here very important. These activities are required to identify deficiencies in and possible modifications of the U.S. technology to the measurement of IPPE materials. Specifically, one aim of the NDA instrumentation evaluation is to determine whether measurement biases are present. This paper presents some preliminary results of our recent evaluation of several high-resolution gamma-ray NDA techniques.

EXPERIMENTAL

A significant part of NDA measurements is the determination of the isotopic content of SNM. There are two types of instruments that measure and analyze the X rays and gamma rays emitted by SNM and are the most widely used in Russia. These are the Canberra U-Pu Inspector and the LANL FRAM Isotopic Analysis System. In addition to these systems, EG&G Ortec is now delivering isotopic analysis systems to some Russian enterprises.

Samples of Pu and U in various forms and with various enrichments were selected and measured with the Canberra U-Pu Inspector and LANL FRAM systems. The data from the U-Pu inspector was analyzed in several ways, depending on the measurement. These include Canberra's MGA9.63 and MGAU codes for Pu and U analysis, respectively. After conversion of the data file, the same data was analyzed with the EG&G Ortec MGA++ and U235 codes for Pu and U, respectively. LANL FRAM v2.2 was used to analyze the data taken with the FRAM system. Some specific characteristics of the codes are:

- Canberra MGA9.63 analyzes Pu and mixed Pu-U in low- and high-energy mode. This code also performs isotope analysis in combination mode (low-energy and high-energy simultaneously using two detectors). MGA-based techniques were developed by Lawrence Livermore National Laboratory (LLNL) many years ago. MGA9.63 is sold and supported by Canberra.
- Canberra MGAU analyzes U in low-energy mode. MGAU was developed at LLNL many years ago. MGAU is sold and supported by Canberra.
- FRAM, version 2.2, analyzes Pu and a wide variety of samples containing Pu, U, Am and other nuclides. This code was developed by LANL many years ago and is also sold by EG&G Ortec.
- Ortec MGA++, which consists of the latest LLNL version of MGA, analyzes Pu and Pu-U mixtures. This code is now supplied by EG&G Ortec. MGA++ also supports a two-detector mode to analyze both low and high-energy gamma-ray spectra simultaneously.
- Ortec U235 analyzes U, was developed by LLNL, and is now supplied by EG&G Ortec.

Experimental Measurement of Pu Samples:

At BFS and CSF, there are a wide variety of SNM containing materials that are used for simulating reactor cores and other experimental activities. For this evaluation, a set of Pu samples was chosen for measurement. Samples containing 95% and 88% ^{239}Pu are in the form of disks covered by 0.3 mm stainless steel. These disks have an average core weight of about 50 grams. Other Pu samples include tubes with a diameter of 6 mm, a height of 145 mm, and an average core weight of about 20 grams. Each sample has a passport (the Russian term for a certificate of the known isotopic content). All measurements were carried out by means of the U-Pu Inspector (the U-Pu Inspector data was converted for analysis by the EG&G Ortec MGA++ code also) and the FRAM system.

The FRAM system consisted of electronic units in a standard NIM BIN and a S100 analyzer. The FRAM system set up was as follows: gain at 0.125 keV per channel, with a shaping time of 2 μsec. The «Coax.8k3» and «SC42» set parameters were used for determination of the isotopic composition of Pu samples. The first set of parameters («Coax.8k3») was used for analyzing the peaks from 120 keV to 451 keV, and for unshielded samples. The second set of parameters («SC42») was used to analyze the region from 203 keV to 780 keV for shielded samples with no gamma-ray peaks below 200 keV.

The U-Pu Inspector was set up for low-energy analysis as follows: gain at 0.075 keV per channel, with a shaping time of 2 μsec. The low-energy set-up characteristics were the same for the Canberra's MGA9.63 and the EG&G Ortec MGA++ analysis because the same data was used for both analyses. The HPGe detector was a planar detector, model GL0510R, with resolution (FWHM) at 122 keV of 550 eV. The low-energy spectra were accumulated with this detector.

The U-Pu Inspector was set up for high-energy analysis as follows: gain at 0.250 keV per channel, with a shaping time of 2 μsec. The HPGe detector for the high-energy acquisitions was a coaxial detector, model GC1818, with a resolution of 680 eV at 122 keV and 1.73 keV at 1332 keV. Spectra with a gain of 0.125 and 0.25 keV/channel were accumulated with this detector. The data from this system were analyzed via both Canberra's MGA9.63 code and (after conversion) the Ortec MGA++ code.

Three types of measurements scenarios were performed. These were:

1. Measurement of select Pu samples under routine measurement conditions (dead time about 20%, live time approximately 30 min),
2. Measurement with varying counting statistics (dead time about 20%, live times of 15, 30, 60 min.),
3. Measurement with varying detector dead time (dead time 20% and 50%, live time about 30 min.).

Each sample was measured five times. The standard deviation of the group of five results for each measurement condition is used as the uncertainty. In the context of these measurements, all of the Pu samples are old. Therefore, the samples contain significant ^{241}Am activity. For this reason, 3 or 4 Cd absorbers (0.3 mm thickness each) were used to reduce the measured activity of the ^{241}Am 59-keV gamma-ray during the measurements of Pu with either the U-Pu Inspector or FRAM systems. The results of the measurements were decay-corrected to the passport date to permit direct comparison to the passport values. Results of the measurement of Pu under the three scenarios mentioned above are presented in Tables 1-8.

Experimental Measurement of U Samples:

A set of U samples was chosen for measurement using the U-Pu Inspector and FRAM systems. The Inspector data was analyzed using Canberra's MGAU, and EG&G Ortec U235. The data acquired with the

FRAM system was analyzed using LANL FRAM version 2.2. The types of U samples measured are presented in a first column of Table 12. Each sample was measured 3 - 10 times in both low-energy and high-energy mode with the U-Pu Inspectors. For the S/100 FRAM measurements, the detector was covered by a special 5-cm Pb collimator. The U-Pu Inspector detector is a planar detector and has its own collimator. The background was about 20 μR/h in the measurement room. Background measurements did not reveal any gamma rays that might influence the measurement results. However, a very small amount of natural Th was observed during long acquisitions of the background. The presence of Th is attributable to the concrete walls and floor of the building.

Measurement times (live) ranged from 1800-2400 seconds for each sample of low enriched (<5%) and high-enriched (>89%) ^{235}U. Measurement time (live) ranged from 1000-1800 seconds for samples with ^{235}U enrichment between 5% and 10%. The dead time was about 20-25% for all measurements. The FWHM of the U-Pu Inspector detector was better than 630 eV at 122 keV. The FWHM of the FRAM detector was better than 1.9 keV at 1332 keV.

RESULTS

Results for Pu Samples and Measurement Scenario 1:

As is shown by the data in Table 1, the Canberra MGA9.63 in the high-energy mode could not analyze the spectra. A low ^{240}Pu content in the sample may be the reason for this. However, the Ortec MGA++ was able to analyze the sample. The most precise results were obtained using MGA9.63 and MGA++ in the low-energy mode.

As is shown in Table, 2, FRAM («Coax.8k3») and Canberra's MGA9.63 in the high-energy mode gave smaller ^{240}Pu content than is indicated in the passport. MGA9.63 (low-energy), FRAM («SC4.2») and Ortec MGA++ agreed with the passport values within the statistics of the measurements.

As is shown in Table 3, FRAM and Canberra's MGA9.63 in the high-energy mode gave smaller ^{240}Pu content than is reported in the passport. The Ortec MGA++ showed good performance for the ^{239}Pu and ^{240}Pu. The ^{241}Pu result was somewhat high.

The results of the measurement of a 77% ^{239}Pu sample are shown in Table 4. It should be noted that this sample contains more than 1% ^{242}Pu. The algorithms available for this evaluation calculate the ^{242}Pu content incorrectly (for this sample). The ^{242}Pu content was declared for all analyses of this sample. The Ortec MGA++ and Canberra MGA9.63 each produced results within 0.5% of the passport values for ^{239}Pu and ^{240}Pu, though the Canberra MGA9.63 result for ^{241}Pu was somewhat high.

The results for a 67% ^{239}Pu sample are shown in Table 5. Again, the ^{242}Pu content was declared for all cases. In the case of Canberra MGA9.63 and Ortec MGA++, the analysis can be modified to better address the high level of ^{242}Pu, but this was done during this evaluation. New parameter sets for FRAM have also been developed that can better address ^{242}Pu, but these were not available for this evaluation.

The results of the measurement of an 89% ^{240}Pu sample are shown in Table 6. All codes did reasonably well on the ^{240}Pu analysis. A new parameter set for FRAM may better address the ^{240}Pu, but this was not available for this evaluation.

The results of the measurement of an 88% ^{238}Pu sample are shown in Table 7. All codes had difficulty with this sample and could not analyze the spectra. One possible explanation for the Canberra MGA9.63 and Ortec MGA++ difficulties is that in the low energy modes, the 129-keV and 208-keV peaks had very low intensity. Neither the Canberra MGA9.63 or FRAM could perform a high-energy analysis on this sample. It should be noted that the Canberra MGA9.63 and Ortec MGA++ codes were never designed to analyze samples with such large ^{238}Pu content. The 152.7-keV gamma ray from ^{238}Pu obscures the 100-keV energy region (Compton) making the analysis very difficult. Other LLNL codes have been developed to analyze such highly enriched ^{238}Pu, but were not part of this evaluation. There is a FRAM parameter set which may better address ^{238}Pu, but this was not available for this evaluation either.

The results of the measurement of a 65.3% ^{241}Pu sample are shown in Table 8. In this case, the Canberra MGA9.63 and FRAM could not analyze the spectra at all. The Ortec MGA++ was able to analyze the data, but the results are not particularly good. However, the EG&G Ortec MGA++ analysis could serve as a confirmatory measurement that the materials was very highly enriched ^{241}Pu. A possible explanation for the Canberra MGA9.63 difficulties was that the low-energy mode can't analyze spectra with a low-intensity 129-keV peak. Possibly because of the high ^{241}Pu (^{241}Am) content, the analyses failed.

The failure of several of these codes for this and some of the other samples illustrates some of the significant differences between materials in the Russian and U.S. inventories. These codes were originally developed for materials in the U.S. inventory only. This is precisely the reason that these measurements need to be made as the measurements provide a means to identify and resolve the problems.

Results for Pu Samples and Measurement Scenario 2:

The second type of experiment was devoted to measurements with different counting statistics (dead time - 20%, live times of 15, 30 and 60 min.). This measurement scenario was useful because of the need to identify the balance point between the required sample measurement time and the expected measurement uncertainty to optimize the PIT process. The results of these measurements are presented in Tables 9–11.

Table 9 shows results of the measurement of a 95.18% ^{239}Pu sample under the conditions of measurement scenario 2 (see above). Not surprisingly, the results improve with increasing counting statistics. The Canberra MGA9.63 low-energy results have generally better statistics owing to the larger gamma-ray branches and detection efficiency in this region. No EG&G MGA++ analyses of this sample was performed. The Ortec MGA++ results would likely be of similar quality to the Canberra MGA9.63 results presented in Table 2.

Table 10 shows the results of the measurement of a 77% ^{239}Pu sample under the conditions of measurement scenario 2. Again, the results improve with increasing counting statistics. No EG&G MGA++ analyses of this sample was performed. The Ortec MGA++ results would likely be of similar quality to the Canberra MGA9.63 results presented in Table 4.

Results for Pu Samples and Measurement Scenario 3:

A third type of experiment was devoted to measurements with different amounts of dead time (dead time 20% and 50%, live time - 30 min.). The results of these experiments indicate that:

1. Both the U-Pu Inspector and FRAM instruments can be operated with low and high amounts of dead time,
2. The FRAM system and the high-energy mode of U-Pu Inspector require an accurate pole-zero correction to obtain satisfactory results,
3. The low-energy mode of U-Pu Inspector accumulates spectra with good peak shape without additional corrections of pole-zero.

Results for U Samples and Measurements:

The measurement conditions, results and passport data are presented in Tables 11 and 12. The following preliminary conclusions can be made:

- All codes perform U analysis well for the samples that ranged between 5% - 10%, and for the samples with thin covers.
- Small values of the standard deviation were obtained for Canberra MGAU and Ortec MGA++ codes for U samples with low ^{235}U content. Larger values of the standard deviation were obtained with the FRAM code. The larger standard deviation in results from the FRAM system may result from the use of the low-intensity 258-keV ^{238}U daughter peak as the efficiency connector between the low-energy and high-energy regions of spectra.
- Small values of the standard deviation were obtained from FRAM for highly enriched U samples. Larger values of the standard deviation were obtained from Canberra's MGAU and Ortec U235 codes for these samples.

The differing relative standard deviations obtained by the codes may be explained by: A) The Canberra MGAU and EG&G Ortec U235 codes use peaks in the 80-100-keV region. This region is a relatively complex multiplet of gamma rays and X rays. For highly-enriched samples the ^{238}U daughter gamma-rays have poor statistics; the ^{238}U peaks are weak in highly enriched materials. This may be the origin of the high uncertainty in the determination of the relative efficiency and statistics in each peak. B) The FRAM code uses the higher-intensity 1001-keV gamma ray to assist in the ^{238}U content determination. This gamma ray is not interfered with by others.

Measurements of U samples with some form of shielding were also performed. Highly-enriched U samples were used for these measurements. Results were obtained using Canberra’s MGAU (2.1a), LANL FRAM and EG&G Ortec U235 codes. Based upon the results shown in Table 11 and Table 12, some conclusions can be made regarding U analysis with Canberra's MGAU, Ortec's U235 and LANL's FRAM:

- All codes produce satisfactory results if the container thickness is small. The measurement results generally agree with the passport data to within about 1%.
- Canberra's MGAU and Ortec's U235 have difficulty if the sample container is thick (>10 mm, steel). Absorption of low-energy peaks in the 100-keV region doesn't permit analysis using these codes. It should be noted that these codes were designed for use with thin containers.
- LANL's FRAM is able analyze spectra of highly shielded U because the code uses higher-energy gamma-rays of U. Satisfactory results were obtained for the sample shielded by 5.5 mm Pb where the dominant ^{235}U gamma-ray line at 185.7 keV is attenuated by about a factor of 1000.

CONCLUSIONS

The results presented here are very preliminary. All three codes work well and can be used for gamma-ray measurements during PIT at IPPE.

An optimal set of gamma-ray instruments and analysis codes should be chosen for each key measurement point. The choice should be based on measurement conditions, types of SNM, and the required level of accuracy of the results within each MBA.

It should be noted that the EG&G Ortec MGA++ operation manual indicates that this code can analyze spectra accumulated by the Canberra multichannel analyzers (CNF expansion) and spectra in ASCII format (without headings). At the present time, this translation mechanism is awkward and should be improved. The standardization of data file formats between acquisition systems would ease this problem.

The Canberra MGA9.63 code can analyze low-energy-only spectra, high-energy-only spectra and combination of low and high-energy spectra for Pu samples (two-detector mode, not evaluated in this report). The Ortec's MGA++ code can analyze low-energy spectra alone and can also be used with a combination of low and high-energy spectra (a two-detector mode, not evaluated in this report). It would be useful to include an independent analysis of high-energy-alone spectra in the Ortec MGA++ code to permit comparison against the Canberra MGA9.63 high-energy-alone analysis. This capability is expected to be available in the near-future.

A new set of analysis parameters should be created for FRAM to permit measurement of materials that contain significant fission product activity. Design of the FRAM code allows the user to change many types of parameters and create custom parameter set for unusual SNM and conditions.

IPPE and US specialists are planning to analyze and compare codes described above further to better resolve some of the measurement issues described in this report.

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Table 1. Measurement results of a sample with 97.7% ^{239}Pu as measured under scenario 1.

	Spectra type	^{239}Pu content, (%)	M. Result / Passport	^{240}Pu content, (%)	M. Result / Passport	^{241}Pu content, (%)	M. Result / Passport
Passport data		97.705		2.243		0.002	
Canberra MGA9.63	Low energy	97.771 ± 0.038	1.001 ± 0.001	2.202 ± 0.054	0.982 ± 0.024	0.022 ± 0.015	11.00 ± 7.50
Canberra MGA9.63	High energy (Pb)	Could not analyze					
FRAM «Coax.8k3»	High energy	97.541 ± 0.808	0.998 ± 0.008	2.372 ± 0.810	1.058 ± 0.361	0.008 ± 0.003	4.00 ± 1.50
FRAM «SC4.2»	High energy (Pb)	98.446 ± 0.650	1.007 ± 0.007	1.491 ± 0.533	0.664 ± 0.238	0.071 ± 0.012	35.50 ± 6.00
Ortec MGA++	Low energy	97.690 ± 0.061	0.999 ± 0.006	2.231 ± 0.062	0.995 ± 0.028	0.069 ± 0.036	34.50 ± 18.50

Table 2. Measurement results of a sample with 95.2% ^{239}Pu as measured under scenario 1.

	Spectra type	Pu^{239} con. (%)	M. Result / Passport	Pu^{240} con. (%)	M. Result / Passport	Pu^{241} con. (%)	M. Result / Passport
Passport data		95.18		4.55		0.26	
Canberra MGA9.63	Low energy	95.15 ± 0.04	0.999 ± 0.001	4.58 ± 0.04	1.006 ± 0.008	0.24 ± 0.08	0.923 ± 0.280
Canberra MGA9.63	High energy (Pb)	95.45 ± 0.18	1.003 ± 0.002	4.31 ± 0.14	0.947 ± 0.031	0.22 ± 0.08	0.846 ± 0.360
FRAM «Coax.8k3»	High energy	95.51 ± 0.11	1.003 ± 0.001	4.19 ± 0.08	0.921 ± 0.019	0.25 ± 0.01	0.962 ± 0.040
FRAM «SC4.2»	High energy (Pb)	95.34 ± 0.19	1.002 ± 0.002	4.35 ± 0.18	0.956 ± 0.041	0.22 ± 0.01	0.846 ± 0.040
Ortec MGA++	Low energy	95.13 ± 0.03	0.999 ± 0.003	4.60 ± 0.16	1.011 ± 0.035	0.26 ± 0.07	0.0 ± 0.26

Table 3. Measurement results of a sample with 88.2% ^{239}Pu as measured under scenario 1.

	Spectra type	^{239}Pu con. (%)	M. Result / Passport	^{240}Pu con. (%)	M. Result / Passport	^{241}Pu con. (%)	M. Result / Passport
Passport data		88.15		10.53		1.04	
Canberra MGA9.63	Low energy	88.49 ± 0.06	1.004 ± 0.007	10.30 ± 0.04	0.978 ± 0.004	1.11 ± 0.02	1.067 ± 0.019
Canberra MGA9.63	High energy (Pb)	88.22 ± 0.04	1.001 ± 0.004	10.63 ± 0.04	1.009 ± 0.004	1.06 ± 0.03	1.019 ± 0.028
FRAM «Coax.8k3»	High energy	88.74 ± 0.11	1.007 ± 0.002	9.94 ± 0.16	0.944 ± 0.016	1.07 ± 0.01	1.029 ± 0.009
FRAM «SC4.2»	High energy (Pb)	88.74 ± 0.26	1.007 ± 0.003	9.94 ± 0.26	0.944 ± 0.016	1.07 ± 0.02	1.029 ± 0.018
Ortec MGA++	Low energy	88.10 ± 0.04	0.999 ± 0.005	10.53 ± 0.04	1.000 ± 0.004	1.24 ± 0.01	1.190 ± 0.009

Table 4. Measurement results of a sample with 77% ^{239}Pu as measured under scenario 1.

	Spectra type	^{239}Pu con. (%)	M. Result / Passport	^{240}Pu con. (%)	M. Result / Passport	^{241}Pu con. (%)	M. Result / Passport
Passport data		77.86		16.76		4.13	
Canberra MGA9.63	Low energy	77.79 ± 0.17	0.999 ± 0.002	16.76 ± 0.15	1.000 ± 0.001	4.21 ± 0.05	1.019 ± 0.012
Canberra MGA9.63	High energy (Pb)	77.68 ± 0.42	0.998 ± 0.005	16.82 ± 0.42	1.004 ± 0.024	4.20 ± 0.14	1.016 ± 0.033
FRAM «Coax.8k3»	High energy	77.15 ± 0.24	0.991 ± 0.003	17.01 ± 0.22	1.015 ± 0.013	4.59 ± 0.05	1.111 ± 0.012
FRAM «SC4.2»	High energy (Pb)	80.41 ± 1.12	1.032 ± 0.014	14.08 ± 1.10	0.840 ± 0.066	4.29 ± 0.22	1.038 ± 0.053
Ortec MGA++	Low energy	77.97 ± 0.13	1.001 ± 0.002	16.67 ± 0.14	0.995 ± 0.008	4.11 ± 0.01	0.995 ± 0.002

Table 5. Measurement results of a sample with 67% ^{239}Pu as measured under scenario 1.

	Spectra type	^{239}Pu con.	M. Result / Passport	^{240}Pu con.	M. Result / Passport	^{241}Pu con.	M. Result / Passport
Passport data		67.59		21.32		7.83	
Canberra MGA9.63	Low energy	67.28 ± 0.27	0.995 ± 0.004	21.28 ± 0.15	0.998 ± 0.007	7.95 ± 0.07	1.015 ± 0.009
Canberra MGA9.63	High energy (Pb)	67.58 ± 0.51	0.999 ± 0.008	21.50 ± 0.34	1.008 ± 0.016	8.08 ± 0.14	1.032 ± 0.018
FRAM «Coax.8k3»	High energy	67.22 ± 0.27	0.995 ± 0.004	20.68 ± 0.29	0.969 ± 0.013	8.03 ± 0.08	1.026 ± 0.010
FRAM «SC4.2»	High energy (Pb)	67.04 ± 0.42	0.992 ± 0.006	21.36 ± 0.36	1.002 ± 0.016	8.51 ± 0.22	1.086 ± 0.028
Ortec MGA++	Low energy	67.54 ± 0.21	1.005 ± 0.003	21.17 ± 0.18	1.002 ± 0.008	8.04 ± 0.04	1.053 ± 0.005

Table 6. Measurement results of a sample with 89% ^{240}Pu as measured under scenario 1.

	Spectra type	^{239}Pu con. (%)	M. Result / Passport	^{240}Pu con. (%)	M. Result / Passport	^{241}Pu con. (%)	M. Result / Passport
Passport data		9.13		89.22		1.49	
Canberra MGA9.63	Low energy	8.88 ± 0.86	0.973 ± 0.010	89.66 ± 0.84	1.004 ± 0.009	1.46 ± 0.12	0.979 ± 0.080
Canberra MGA9.63	High energy (Pb)	9.28 ± 0.68	1.016 ± 0.073	89.17 ± 0.65	0.999 ± 0.017	1.51 ± 0.14	1.013 ± 0.093
FRAM «Coax.8k3»	High energy	8.26 ± 0.78	0.905 ± 0.095	90.08 ± 0.69	1.009 ± 0.007	1.51 ± 0.09	1.013 ± 0.059
FRAM «SC4.2»	High energy (Pb)	9.81 ± 1.10	1.074 ± 0.111	88.37 ± 1.08	0.991 ± 0.012	1.57 ± 0.22	1.054 ± 0.047
Ortec MGA++	Low energy	8.78 ± 0.54	1.071 ± 0.059	89.71 ± 0.56	1.005 ± 0.006	1.51 ± 0.01	1.013 ± 0.006

Table 7. Measurement results of a sample with 87.98% ^{238}Pu as measured under scenario 1.

	Spectra type	^{238}Pu con. (%)	^{239}Pu con. (%)	^{240}Pu con. (%)	^{241}Pu con. (%)	^{242}Pu con. (%)
Passport data		87.98	9.12	2.53	0.32	0.05
Canberra MGA9.63	Low energy	Can't analyze				
Canberra MGA9.63	High energy (Pb)	Can't analyze				
FRAM «Coax.8k3»	High energy	Can't analyze				
FRAM «SC4.2»	High energy (Pb)	Can't analyze				
Ortec MGA++	Low energy	Can't analyze				

Table 8. Measurement results of a sample with 65.3% ^{241}Pu as measured under scenario 1.

	Spectra type	^{238}Pu con. (%)	^{239}Pu con. (%)	^{240}Pu con. (%)	^{241}Pu con. (%)	^{242}Pu con. (%)
Passport data		-	0.98	21.98	65.30	11.74
Canberra MGA9.63	Low energy	Can't analyze				
Canberra MGA9.63	High energy (Pb)	Can't analyze				
FRAM «Coax.8k3»	High energy	Can't analyze				
FRAM «SC4.2»	High energy (Pb)	Can't analyze				
Ortec MGA++	Low energy	0.07 ± 47.67	4.36 ± 138.02	26.71 ± 9.05	57.11 ± 8.01	*11.74 ± (10%)

Table 9. Measurement results of a sample with 95.18% ^{239}Pu as measured under scenario 2. Note that the EG&G Ortec MGA++ analysis was not performed for this sample and the interpretation may be different between the Canberra MGA9.63 and the Ortec MGA++.

	Meas. Live time (min.)	Spectra type	^{239}Pu content, (%)	M. Result / Passport	^{240}Pu content, (%)	M. Result / Passport	^{241}Pu content, (%)	M. Result / Passport
Passport			95.18		4.55		0.27	
Canberra MGA9.63	15	Low energy only	95.16 ± 0.48	0.994 ± 0.001	4.56 ± 0.48	1.001 ± 0.010	0.25 ± 0.12	0.923 ± 0.444
	30		95.15 ± 0.04	0.999 ± 0.001	4.58 ± 0.04	1.006 ± 0.008	0.24 ± 0.08	0.889 ± 0.280
	60		95.16 ± 0.02	0.999 ± 0.001	4.56 ± 0.02	1.001 ± 0.004	0.26 ± 0.04	0.963 ± 0.148
Canberra MGA9.63	15	High energy (3mm Pb)	95.80 ± 0.64	1.007 ± 0.001	3.98 ± 0.64	0.874 ± 0.141	0.20 ± 0.14	0.741 ± 0.518
	30		95.45 ± 0.18	1.003 ± 0.002	4.31 ± 0.14	0.947 ± 0.031	0.22 ± 0.08	0.846 ± 0.360
	60		95.18 ± 0.08	1.000 ± 0.001	4.48 ± 0.08	0.984 ± 0.020	0.26 ± 0.01	0.963 ± 0.037
FRAM «Coax.8k»	15	High energy	96.44 ± 0.23	1.013 ± 0.002	3.27 ± 0.24	0.718 ± 0.051	0.20 ± 0.04	0.741 ± 0.148
	30		95.51 ± 0.11	1.003 ± 0.001	4.19 ± 0.08	0.921 ± 0.019	0.25 ± 0.01	0.962 ± 0.040
	60		95.33 ± 0.08	1.001 ± 0.001	4.37 ± 0.08	0.970 ± 0.017	0.22 ± 0.02	0.815 ± 0.074
FRAM «SC4.2»	15	High energy	95.43 ± 0.26	1.002 ± 0.001	4.36 ± 0.26	0.970 ± 0.050	0.20 ± 0.02	0.741 ± 0.074
	30		95.34 ± 0.19	1.002 ± 0.002	4.35 ± 0.18	0.956 ± 0.041	0.22 ± 0.01	0.846 ± 0.040

Table 10. Measurement results of a sample with 77% ^{239}Pu as measured under scenario 2. Note that the EG&G Ortec MGA++ analysis was not performed for this sample and the interpretation may be different between Canberra's MGA9.63 and Ortec's MGA++.

	Meas. Live time (min.)	Spectra type	^{239}Pu content, (%)	M. Result / Passport (%)	^{240}Pu content, (%)	M. Result / Passport (%)	^{241}Pu content, (%)	M. Result / Passport (%)
Passport			77.86		16.76		4.13	
Canberra MGA9.63	15	Low Energy	77.73 ± 0.25	0.998 ± 0.003	16.82 ± 0.19	1.004 ± 0.011	4.22 ± 0.08	1.022 ± 0.019
	30		77.79 ± 0.17	0.999 ± 0.002	16.76 ± 0.15	1.000 ± 0.001	4.21 ± 0.05	1.019 ± 0.012
Canberra MGA9.63	15	High energy (3.5 mm Pb)	77.84 ± 0.43	0.999 ± 0.005	16.71 ± 0.41	0.997 ± 0.020	4.21 ± 0.17	1.019 ± 0.041
	30		77.68 ± 0.42	0.998 ± 0.005	16.82 ± 0.42	1.004 ± 0.024	4.20 ± 0.14	1.016 ± 0.033
FRAM «Coax.8k»	15	High Energy	76.02 ± 0.67	0.976 ± 0.009	18.12 ± 0.66	1.081 ± 0.039	4.60 ± 0.12	1.138 ± 0.029
	30		77.15 ± 0.24	0.991 ± 0.003	17.01 ± 0.22	1.015 ± 0.013	4.59 ± 0.05	1.111 ± 0.012
	60		77.03 ± 0.16	0.989 ± 0.002	17.09 ± 0.12	1.019 ± 0.007	4.63 ± 0.04	1.121 ± 0.010
FRAM «SC4.2»	15	High energy (3.5 mm Pb)	78.75 ± 2.44	1.003 ± 0.031	15.81 ± 2.52	0.943 ± 0.150	4.23 ± 0.24	1.024 ± 0.058
	30		80.41 ± 1.12	1.032 ± 0.014	14.08 ± 1.10	0.840 ± 0.066	4.29 ± 0.22	1.038 ± 0.053
	60		79.77 ± 0.46	1.024 ± 0.006	14.68 ± 0.44	0.876 ± 0.026	4.31 ± 0.11	1.043 ± 0.026

Table 11. Measurement results for U samples with varying enrichment. The ^{235}U content varies from 0.72% to 99.8%.

		System (code)						
		Canberra MGAU		Ortec U235		LANL FRAM		
Sample	^{235}U (%) Passport	^{235}U (%)	M. result / Passport	^{235}U (%)	M. result / Passport	^{235}U (%)	M. result / Passport	Set param.
UO_2, 10g 3mm Al container	0.72	0.80 ± 0.04	1.12 ± 0.05	0.82 ± 0.07	1.14 ± 0.09	0.82 ± 0.49	1.15 ± 0.68	Low. Enrich.
UO_2, 20g 3mm Al container	5.00	5.01 ± 0.01	1.00 ± 0.00	4.95 ± 0.01	0.99 ± 0.01	4.60 ± 0.74	0.92 ± 0.15	Low. Enrich.
UO_2, 3.5kg 3mm steel container	10.00	9.86 ± 0.20	0.99 ± 0.02	9.75 ± 0.24	0.98 ± 0.02	9.53 ± 0.43	0.95 ± 0.04	Low. Enrich.
U, 150g 0.3mm steel container	89.21	90.29 ± 1.40	1.01 ± 0.02	89.85 ± 1.35	1.01 ± 0.02	88.92 ± 0.83	0.99 ± 0.01	High Enrich.
UO_2, 2g 0.3mm steel container	99.8	Can't analyze		Can't analyze		99.39 ± 0.80	0.99 ± 0.01	High Enrich.
MODE		Low energy only		Low energy only				

Table 12. Measurement results for a U sample through different shields. The ^{235}U content is 89.21%.

	System (code)						
	Canberra MGAU		Ortec U235		LANL FRAM		
Filter type (material, Thickness in mm)	^{235}U (%)	M. result / Passport	^{235}U (%)	M. result / Passport	^{235}U (%)	M. result / Passport	Set param.
Steel, 0.3mm	90.29 ± 1.40	1.01 ± 0.02	89.85 ± 1.35	1.01 ± 0.02	88.92 ± 0.83	0.99 ± 0.01	High Enrich.
Steel, 4.3mm	84.80 ± 1.95	0.95 ± 0.02	87.16 ± 2.01	0.98 ± 0.02	89.90 ± 0.92	1.01 ± 0.01	High Enrich.
Steel, 11mm	81.50 ± 6.72	0.91 ± 0.07	Can't analyze		89.57 ± 0.68	1.01 ± 0.01	High Enrich.
Steel, 15mm	Can't analyze		Can't analyze		88.99 ± 0.80	0.99 ± 0.01	High Enrich.
Pb, 5.5mm & Steel, 2mm	Can't analyze		Can't analyze		84.21 ± 1.35	0.94 ± 0.01	High Enrich.
Mode	Low energy only		Low energy only				